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KSTAR Application for Fast Neutron Radiography

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1. Introduction

1.1 Neutron Radiation of KSTAR

Korea Superconducting Tokamak Advanced Research (KSTAR) is a magnetic fusion device being built at the National Fusion Research Institute in Daejon, Korea. After the successful first operation in 2008 [1], the plasma performance is enhanced and duration of H-mode is extended to around 50 sec. In addition to long-pulse operation, the operational boundary of the H-mode discharge is extended over MHD no-wall limit (β_N~4) transiently and higher stored energy region is obtained by total heating power of ~6 MW and plasma current up to 1 MA for ~10s.[2]

Because of the increased heating power of the plasma with the neutral beam (NB) of 100keV with 4.5 MW, neutron generation has been increased from D-D fusion reaction in the plasma. The report of KSTAR 2011 campaign says that the neutron flux at the irradiation station was 2.2×10^8 /cm^2/s, and the total neutron yield was 4.7×10^{13} n/s for a typical NBI-heated, H-mode KSTAR plasma shot.[3,4] So, the analysis and application of the neutron radiation are in need.

1.2 Fast Neutron Radiography

As one of the applications of the neutron radiation, neutron radiography is similar to, and complementary to, radiography using x-rays. However, neutrons, being sensitive to the nuclear properties of materials, provide information fundamentally different from x-rays. So, neutron imaging is a powerful non-destructive evaluation (NDE) technique that uses the penetrability of neutrons to image details in low-Z materials that are heavily shielded by high-density, high-Z materials. Such configurations are challenge cases for x-ray radiography since the high-Z surrounding “hardens” a typical bremsstrahlung x-ray spectrum from an electron stopping target, and it is the lower energy photons that are lost that are needed to image the low-Z materials inside.[5, 6] Neutron radiography has found its greatest applications in the examination of nuclear fuels, explosives, electronic components and engine turbines blades. Recently, neutron imaging has been used in new branches: fuel cell research, the study of objects from cultural heritage, geoscience and soil physics.

Strong neutron sources like research reactors and accelerator-based spallation neutron sources, has provided intense neutron beams, required for efficient and practical neutron imaging. Since neutrons generated from KSTAR is examined to be fast neutrons of ~2.4 MeV [3, 4], fast neutrons have great advantages in penetration depth [7]. Neutron radiography using fast neutrons from KSTAR is planned to be set up. Here the setup for the first stage is presented.

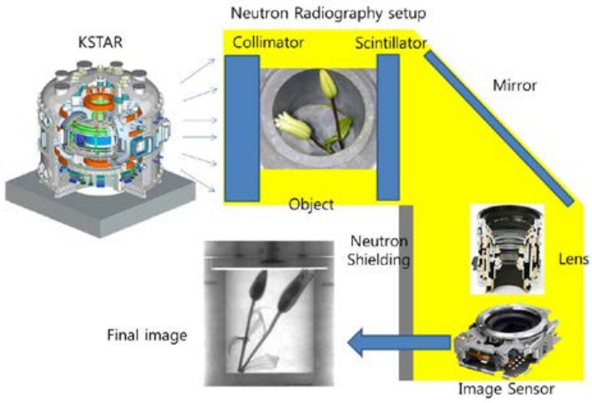

Figure 1. Schematic diagram of radiography setup using KSTAR neutrons

2. Conceptual Setup Design

The schematic diagram of the setup for the radiography using KSTAR neutron is shown in figure 1. The setup has a collimator for a parallel neutron beam, an object for measurements, a scintillator for converting neutron density to visible light intensity, a mirror for bending the beam path by 90 degree and a visible camera set including a lens set and an image sensor module. The 90 bending mirror makes the image sensor protected from the neutron radiations exposure since the image sensor is off-located from the neutron beam path and it can be shielded.

Since the neutron radiations from KSTAR have not been fully examined in radiation intensity profile or particle energy distribution at this stage, the setup is not designed for the optimum design or challenging goals, rather it is based on the typical design as shown in Figure 1. However, KSTAR generate fast neutrons with high energy of ~ 2.4 MeV as Ref. 3 and 4. It can extend the radiography area with high penetration of the fast neutrons from KSTAR.

The neutrons are assumed to be radiated isotropic from plasma of KSTAR. So, the middle ports are appropriate for the installation of the setup since the radiation direction is radial and parallel to the deck of the middle ports. If not, the setup needs to be tilted or aligned along the slanted direction. The collimator is a neutron shielding pipe covering 20 x 20 cm^2 of measurement area. The collimator selects the parallel beams along the pipe by blocking the undesirable beams degrading image resolution.

As for the radiation shielding, the most radiations are combinations of different kinds of radiation, such as fast neutrons, thermal neutrons, primary gamma and secondary gamma rays. Fast neutrons are most effectively shielded by materials with high hydrogen content. They are slowed to thermal energies by collision with hydrogen atoms. Thermal neutrons can be virtually eliminated by the presence of high thermal neutron cross-section materials such as boron. Primary gamma rays are best shielded with lead or other high density materials. Secondary gamma rays are created as the result of the capture of thermal neutrons by hydrogen. These capture-gamma rays can be minimized by adding boron. Thus, the collimator is to be made of borated High Molecular Weight Polyethylene (HMWP), and the camera shielding blocks are made of combinations of HMWP and lead plates.

BC-4xx series of Bicron® will be examined for the scintillator. They are polyvinytoluene base plastic scintillators for fast neutron. For the alternative candidates, polypropylene-based scintillators will be also examined. Scintillator is the most difficult part to be fixed since the resolution and conversion efficiency depends on its thickness and the material type. And the exact neutron profile from KSTAR is not fully examined. Final model will be fixed after several experiments.

The converted visible lights through the scintillator are collected by lens module. The lens module also decides the image quality (spatial resolution, brightness, intensity uniformity) of the radiography. To collect the converted light from neutron particles effectively, the entrance aperture of the lens module is better to be as big as possible. So, f-number of the lens module gets to be relatively small. However, Because of TV-distortion and intensity reduction at the edge region of image, the degradation at image edge is inevitable. To minimize this effect, a focus length of the lens module needs to be relatively long. Thus, lens size, focus lens and cost are considered adding on the compatibility with image sensor for the light collection. For the first step, Nikon lens module (50 mm of focus length and f-number of 1.2) was chosen rather than a customized lens module.

In digital imaging sensors, CCD type and CMOS type are available, but CCD camera module covers most neutron imaging needs as shown in Figure 2. The biggest difference of them is that CCD sensors create high quality images with low noise. CMOS usually has a fast frame rate, but CMOS sensors need more light to create a low noise image at proper exposure as shown in Figure 2. In typical neutron imaging, signal noise control is a big issue and an image sensor need to be cooled down since neutron imaging works under the low luminance from a scintillator. For the first step of the neutron radiography, Artemis LF40+ CCD camera was chosen. It features the KAI-04022 Kodak sensor with 2048 x 2048 resolution pixels.

3. Summary

The neutrons from KSTAR had been reported to be radiated with the flux of ~2.2×10^8 /cm^2/s and energy of ~2.4 MeV. The radiography using KSTAR fast neutrons is planned as its application. The basic design of the setup, based on the typical configuration, was decided for the first step of the experiments. Several type of scintillator is being ready to be examined for the best performance. The first setup will be applied in KSTAR 2015 campaign, and it can characterize the neutron radiation from KSTAR. Based on the data, the optimum design of the setup for fast radiography can be derived.

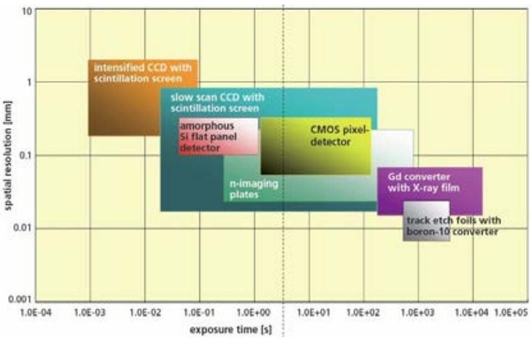

Figure 2. Image sensor application area for neutron radiography [8]

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